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Tribological Behavior of PTFE, PEEK, and Fluorocarbon-based Polymeric Coatings used in Air-Conditioning and Refrigeration Compressors

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ABSTRACT

Technological advances in materials and coating deposition techniques has made it possible to coat different substrate materials used in air-conditioning and refrigeration compressors, with advanced blended polymeric coatings based on Polyetheretherketone (PEEK) and Polytetrafluoroethylene (PTFE). PEEK and PTFE can also be blended together and along with solid lubricants (such as graphite and Molybdenum Disulfide, MoS_2) to improve friction and wear behavior. In this work, boundary and mixed lubricated experiments were performed using a high pressure tribometer, simulating realistic compressor conditions. Specifically four different polymeric coatings of several tens of microns thickness were tested: PTFE/MoS_2, Fluorocarbon resin, PEEK/PTFE, and PEEK/Ceramic/PTFE blends were tested against 52100 steel crowned pins. A mixture of hydrofluorocarbon R-134a refrigerant and polyalkylene glycol lubricant were sprayed at the sliding interface. Experimental results showed that the PEEK/PTFE coating performed slightly better in terms of friction and wear, compared to the other polymeric coatings. Such polymeric-based coatings, which are somewhat inexpensive and can be readily coated to compressor substrate materials, offer significant tribological improvements compared to uncoated surfaces and are viable material systems for compressors.

1. INTRODUCTION

Air-conditioning and refrigeration research has been shifting attention towards advanced compressors with the ultimate goal of developing advanced oil-less compressors, partly due to adverse thermodynamic effects of the oil present in the refrigeration cycle and the added complexity to the system. Development of oil-less compressors require the search of advanced materials, able to withstand unlubricated sliding conditions while maintaining friction and wear at acceptable levels. Significant technological advances on the application and deposition of polymeric coating materials have been seen in the last decade. Spray techniques and Chemical Vapor Deposition has made possible the reliable deposition of 10's of microns thick polymeric coatings based on PTFE, PEEK, and Fluorocarbons onto substrates that posses low surface energy such as gray cast iron. PTFE is characterized by low friction coefficient and high wear rates. It is believed that the low friction coefficient displayed by PTFE during sliding is related to the low shear strength of its long -(CF_2-CF_2)- chains (Sawyer et al (2003)-based on bulk studies). This low friction coefficient along with its high melting point (327 °C) makes this polymer attractive for unlubricated sliding applications (Blanchet and Kennedy (1992)). However, the continuous transfer of PTFE layers to the counterface and its easy removal makes the wear rates of this material unacceptably high (Tanaka et al. (1973)). PEEK on the other hand, is a thermoplastic polymer that can be blended with PTFE to improve its wear performance. The good wear resistance of PEEK can be attributed to its stiff backbone chemical structure and high temperature stability which includes high melting point (335 °C) and high glass transition temperature (145 °C) as reported by Blundell and Osborn (1983). Lu and Friedrich (1995) showed that friction coefficient and wear rate values of blends of PEEK and PTFE (in bulk form) have minimum values when the blends contain 10-20% PTFE. They concluded that 15% partial volume of PTFE was optimum to obtain low values of friction and wear under sliding conditions of 1 m s^{-1} and 1 MPa contact pressure. They explained that this reduction on friction and wear was due to the transfer of a continuous layer to the steel counter face. It was reported that at this volume, a continuous phase of PEEK with PTFE particles was present. The PTFE particles are responsible for the low friction (continuous transfer film) while the PEEK structure still provides good strength and wear resistance. The abovementioned studies were for bulk polymer blends (not as coatings), which pose difficulties as direct compressor interface material replacements. Relatively few published tribological studies exist dealing with polymeric materials in refrigerant environments. Cannaday and Polycarpou (2005) reported that blended PTFE polymers were suitable for applications where low friction and low wear are required, but only in situations of low normal loads. In situations with high starting normal loads, PEEK blends where found to be more suitable compared to PTFE blends.

Despite the fact that the studies previously mentioned provide answers of the friction and wear behavior of PTFE and PEEK blends, tribological studies related to the performance of these polymers deposited onto substrates are limited. For instance, Shaffer and Rogers (2007) found that a PTFE/MoS_2 based polymeric coating showed a friction coefficient below 0.2 along with a prolonged wear life in a range of temperatures from ambient up to 150 °C under unlubricated conditions. They reported that this commercially available polymeric coating can be potentially applied to small arm components that require absence of lubricant. Recent work in the presence of refrigerant was reported by Demas and Polycarpou (2008), where they compared the tribological performance of three different commercially available PTFE-based polymeric coatings. Namely, they studied two different PTFE/pyrrolidone coatings and a PTFE/MoS_2. These coatings were coated onto gray cast iron and tested under unlubricated oscillatory conditions. They found that during testing, the thickness of the coating was rapidly penetrated and most of the wear took place during the first two minutes of the test. In spite of the fact that the coatings were penetrated, they reported that the wear debris behaved as a third body and avoided scuffing, performing better than state-of-the art hard diamond-like carbon coatings. In a continuation of the aforementioned study, Dascalescu et al. (2009) evaluated the effect of the substrate on the performance of the same three coatings. By using X-ray Photoelectron Spectroscopy (XPS) it was shown that in fact, the PTFE/MoS_2 coating was the only coating which did not show any sign of scuffing when coated on Al390-T6 substrate. They found that the metal fluorides formed as a result of fragmentation of PTFE and its interaction with the Al390-T6 substrate had a positive effect on the performance of PTFE/MoS_2 by improving its adhesion to the substrate.

Even though there are some studies on the performance of commercially available PTFE and PEEK deposited coatings in the presence of refrigerant), studies dealing with their friction and wear response in the presence of lubricant (in addition to refrigerant) is missing. The objective of this study is to measure the friction and wear behavior of different PTFE/MoS_2, Fluorocarbon, PEEK/PTFE, and PEEK/Ceramic/PTFE blend polymeric coatings under aggressive boundary/mixed unidirectional sliding conditions at high temperature. Experimental findings were supported by Scanning Electron Microscopy (SEM) analysis.

2. EXPERIMENTAL SETUP

2.1 High Pressure Tribometer

A High Pressure Tribometer (HPT) was used to perform controlled tribological experiments. The HPT uses an upper rotating sample in contact with a lower stationary sample/holder system. Tribological experiments were carried out using a pin-on-disk configuration where the pin was the lower stationary component and the disk the upper rotating part. The lower pin and upper disk are brought into contact by using a mechanical screw and the stationary lower part is connected to a 6-axis force transducer capable of measuring normal loads up to 4450 N and friction forces up to 2225 N. The spindle (upper part) can be controlled at amplitudes of $\pm 180^{\circ}$ and frequencies up to 5 Hz in the oscillatory mode while 2000 rpm is the maximum rotational speed in the unidirectional mode. More details of the technical specifications of this equipment can be found in Cavatorta and Cusano (2000).

2.2 Coating Samples and Experimental Conditions

Gray cast iron samples (which is a material commonly used in scroll-type compressors) were coated by an authorized vendor. The coatings were applied using a spray gum which deposits the coating on a previously treated substrate. The substrate is grid-blasted using an 80-grit aluminum oxide abrasive which provides a stippled surface for good mechanical bonding of the deposited coating (typically a blasting pressure between 40-60 psi is used). After deposition of the coating, everything in the mix goes away by curing or baking. After this step, only solid components are left on the deposited coating. During this study, a set of wear (constant load) experiments was performed. Four different commercially available soft polymeric coatings deposited on gray cast iron disks were tested. Namely, PTFE/MoS_2, Fluorocarbon resin, PEEK/PTFE, and PEEK/PTFE/Ceramic blend. Table 1 shows the cure and in-use temperature of these coatings along with their typical physical color. The diameter of the disk samples was 76 mm and had an initial surface roughness (Rq) of approximately 0.2-0.4 μm before grid blasting. These roughness measurements were performed using a contact profilometer. The pins (lower stationary part) were original pins (or shoes) used in typical swash plate type compressors. They were made of 52100 hardened steel and were placed on a self aligned pin-holder to ensure that the contact remained flat. The contact configuration is seen in Figure 1. The shoe has a hole drilled to 2 mm below the surface to measure the near-contact temperature during testing. The mixture of PAG lubricant and refrigerant was sprayed at the sliding interface using a nozzle as seen in Figure 1c.

Table 1: Polymeric coatings

Polymer Coating	**PTFE/MoS_2**	**Fluorocarbon**	**PEEK/PTFE**	**PEEK/PTFE/Ceramic**
Cure temperature (°C)	316	316	400	400
In-use temperature (°C)	260	232	260	260
Color	Dark-green	Black	Light-blue	Beige-tan

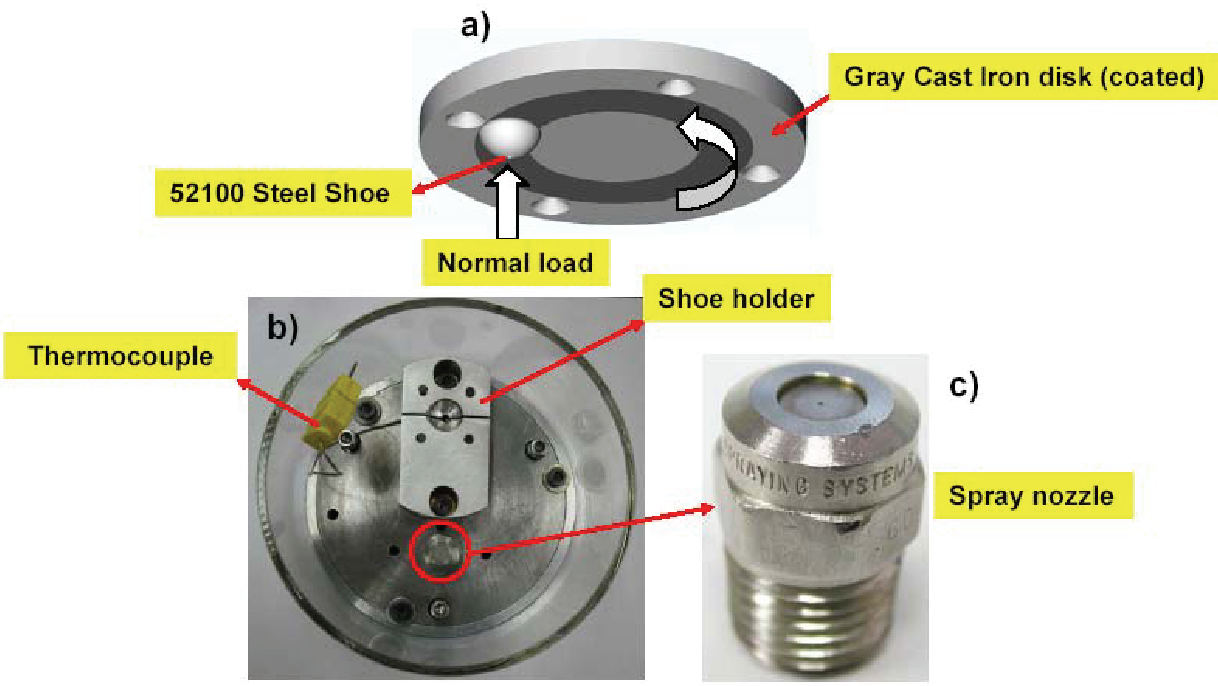

Figure 1: Sample configuration used in tribological tests. a) Disk and self-aligned shoe, b) Thermocouple, shoe-holder, and c) atomizing spray nozzle.

Using the HPT, a set of constant load (wear) experiments was performed. During these experiments, Tetrafluoroethane (R-134a) refrigerant was mixed with Polyalkylene glycol (PAG) lubricant and sprayed at the sliding interface using a pressure nozzle at a rate of approximately 20 mg/min. The normal load was kept constant at 445 N and the test duration was 30 mins. A rotational speed of 2000 rpm, corresponding to a linear speed of 4.8 m/s was used and the pressure of the R-134a/PAG mixture was kept constant at 0.17 MPa (25 psi). The temperature of the chamber was kept constant at 100 °C. Before initiating a test, the coated disks were immersed in a pool of alcohol while the shoes were submerged in acetone and cleaned ultrasonically, and then both; coated disks and shoes were rinsed with alcohol and dried using warm air. The testing conditions are summarized in Table 2.

Table 2: Summary of experimental conditions of wear tests

Parameters	Experimental conditions
Chamber pressure: (MPa)	0.17
Temperature (°C)	100
Normal load (N)	100
Time (s)	1800
Lubricant supply rate (mg/s)	20
Linear Speed (m/s)	4.8

3. EXPERIMENTAL RESULTS

3.1 Measurements of Coating Thickness

The thickness of the coatings was measured by cross section SEM. Representative thickness values of the four coatings used in the experiments are shown in Figure 2. As can be observed, the thickness of these coatings is not absolutely uniform throughout the cross section and the approximate thicknesses were found to be 40, 20, 25, and 36 μm for the PEEK/PTFE, PTFE/MoS_2, Fluorocarbon, and PEEK/PTFE/Ceramic, respectively.

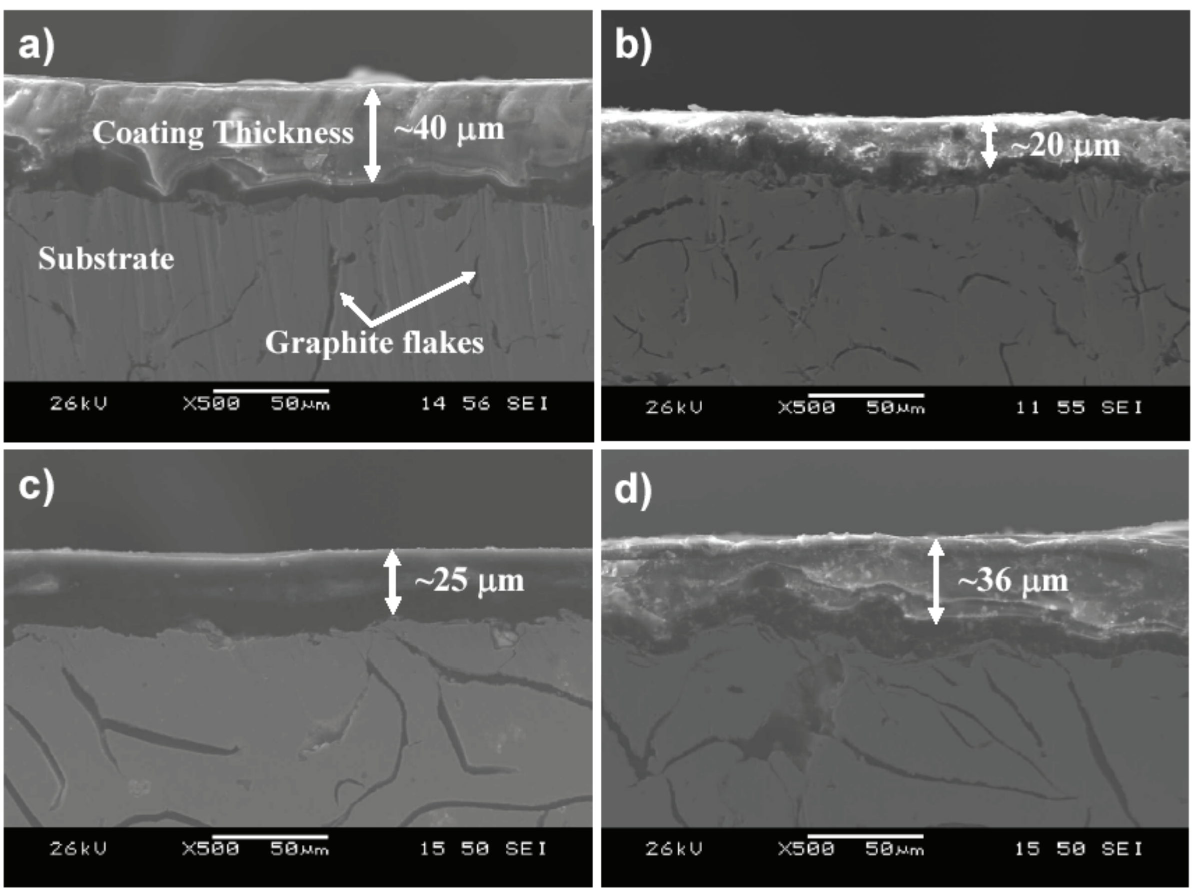

Figure 2: Cross section SEM images of the different coated disks. a) PEEK/PTFE, b) PTFE/MoS_2, c) Fluorocarbon, d) PEEK/PTFE/Ceramic.

3.2 Tribological Testing

Representative experimental results are depicted in Figure 3. As can be observed in Figure 3a, the steady state value of the friction coefficient for the case of PEEK/PTFE coated disk was approximately 0.07 (note that at least two experiments were performed for each case showing good repeatability). The friction coefficient was slightly higher at ~0.09 in the case of PTFE/MoS_2 (Figure 3c) and approximately 0.06 in the case of PEEK/PTFE/Ceramic (Figure 3g). In the case of the Fluorocarbon coating, the interface scuffed after approximately 2874 m of sliding distance as seen in Figure 3e due to penetration of the coating. Interestingly in all the coated samples, except the Fluorocarbon the near contact temperature was increased during the initial stages of the experiments and then decreased until the end of the tests (see Figure 3b, d, and h). These phenomena can be explained based on the transfer films from the soft polymeric coatings to the hard 52100 steel counterface. Figure 4a and b show patchy dark regions (PTFE material) of transfer material to the surface of the shoe in the case of the PTFE/MoS_2 coated disk. One explanation of the temperature behavior is that once these transfer films are deposited, on the shoe they act as a thermal barrier (insulators) thus decreasing the near contact temperature measured 2 mm below the surface of the shoe (note that the friction behavior is stable throughout the experiments and does not follow the near contact temperature trends). In all three successful cases the maximum peak near contact temperature was ~190 °C which is lower than the in-use temperature listed in Table 1. However, in the case of Fluorocarbon the near contact temperature reached a maximum of approximately 230 °C, which is close to the maximum in-use temperature of this coating.

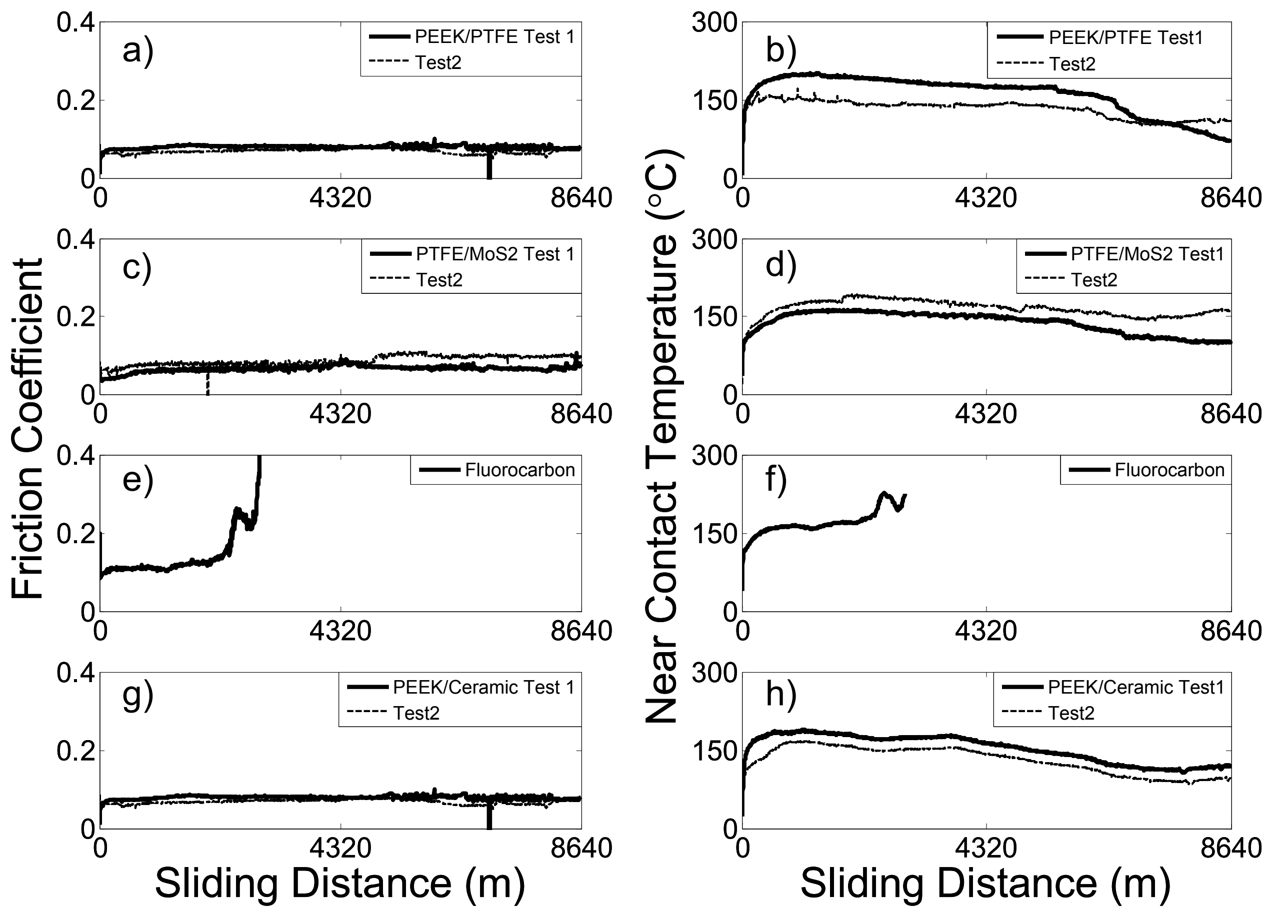

Figure 3: Typical experimental results depicting friction coefficient and near contact temperature for (a), (b) PEEK/PTFE, (c), (d) PTFE/MoS_2, (e), (f) Fluorocarbon, and (g), (h) PEEK/PTFE/Ceramic.

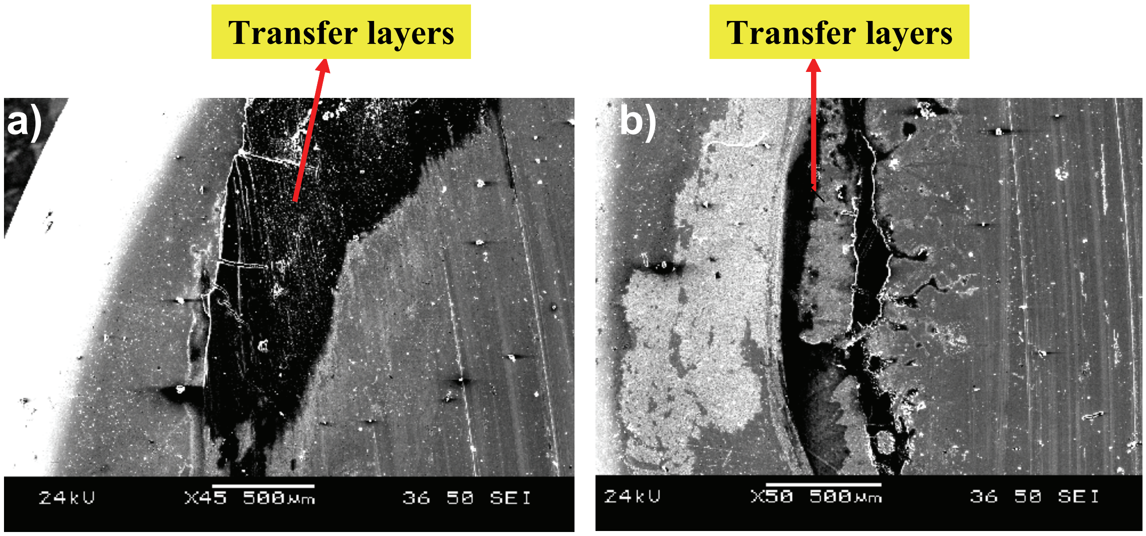

Figure 4: SEM images of the 52100 steel shoes tested against PTFE/MoS_2 where (a) and (b) show two different regions on the surface of the 52100 steel pin.

After tribotesting, the wear of the different coated disks was measured using a contact profilometer. The wear scans were 12 mm long to capture the variation in surface height from the untested to the tested region. As seen in Figure 5a the PEEK/PTFE coating only showed mild burnishing (i.e., there is no measurable wear). In the case of PTFE/MoS_2 the wear depth was ~3 µm with some isolated deeper wear "scars" of ~8 µm as seen in Figure 5b. In the case of Fluorocarbon the average wear depth was ~30 µm and the deeper wear scars ~50 µm (Figure 5c). It is evident that in the case of Fluorocarbon the coatings was penetrated and the reason why scuffing occurred. PEEK/PTFE/Ceramic showed a wear depth of ~10 µm and wear scars ~40 µm deep (Figure 5d). In this case, it is interesting to observe that even though the wear scars were slightly deeper compared to the thickness of the coating (see Figure 2d)) no sign of scuffing was seen during the experiments.

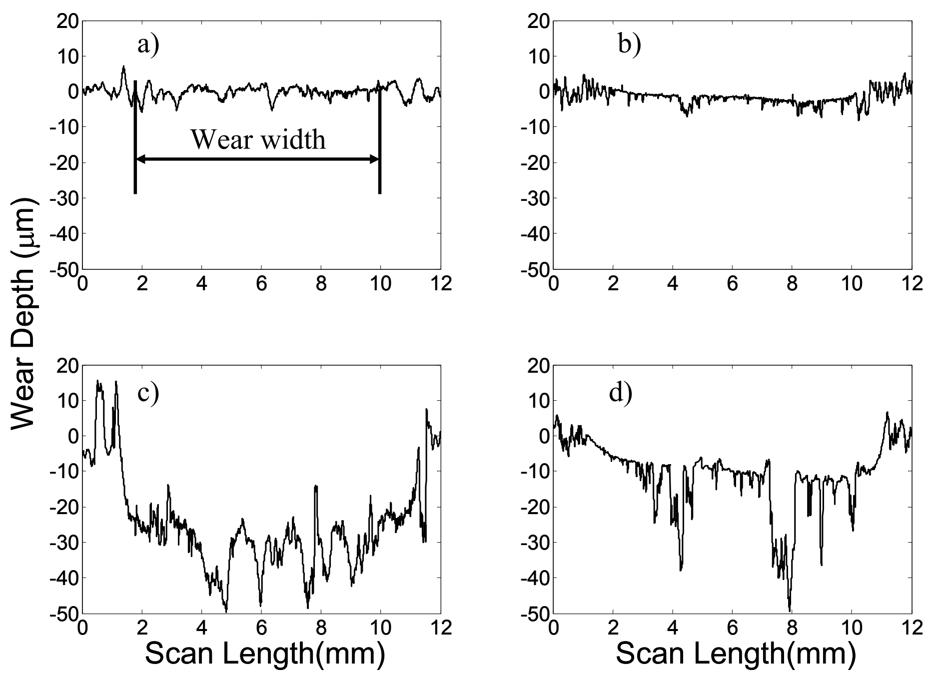

Figure 5: Profilometric wear measurements, (a) PEEK/PTFE, (b) PTFE/MoS_2, (c) Fluorocarbon, and (d) PEEK/PTFE/Ceramic.

Based on the above wear measurements, we calculated the wear rate of the three best performing coatings (Fluorocarbon was excluded due to the fact that scuffed) and compared their wear and friction behavior, as shown in Figure 6. It can be seen that PEEK/PTFE performs better in terms of wear and friction coefficient vs PEEK/PTFE/Ceramic and PTFE/MoS_2. Note that the reported wear rates of less than 2 x10^{-6} mm^3/Nm are very small and comparable to the best performing composite bulk materials (and even hard coatings). Along with low friction coefficient, the properties of these coatings makes then excellent candidates for compressor applications.

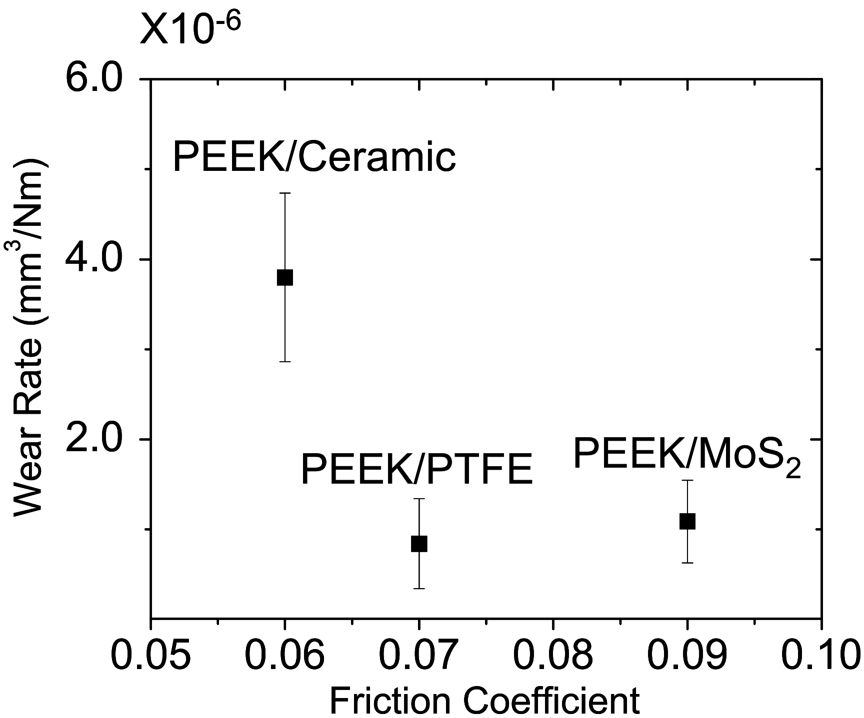

Figure 6: Wear rate vs friction coefficient of the three best performing coatings during boundary/mixed lubrication conditions.

5. CONCLUSIONS

The performance of four different commercially available soft polymeric coatings under boundary-mixed lubrication conditions was studied. Experimental results showed that the disks coated with PEEK/PTFE performed better in terms of both wear and friction compared to PEEK/MoS_2 (which comes close second) and PEEK/PTFE/Ceramic, thus making these coatings attractive for aggressive sliding conditions. The fluorocarbon coating on the other hand was unable to withstand the same aggressive conditions. Despite the aggressive tribological conditions, including high temperature testing, the transfer of films from the disk coating to the hard surface of the 52100 steel shoes, enable the interface to operate without overheating.

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